1. IC6.5 Part 1: Snowfall Forecasting

Instructor Notes: Welcome to IC 6, Lesson 5: Snowfall Forecasting.

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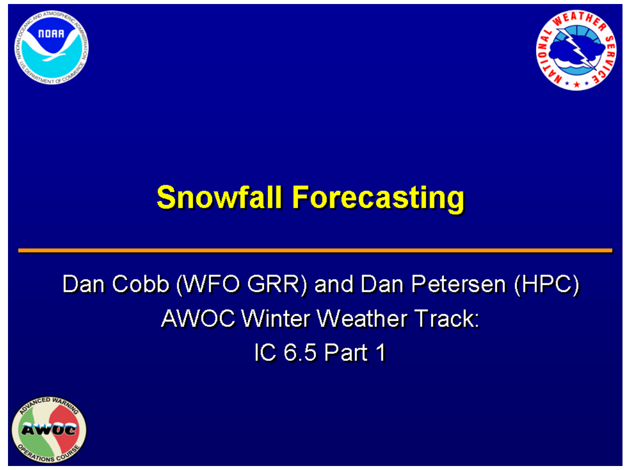
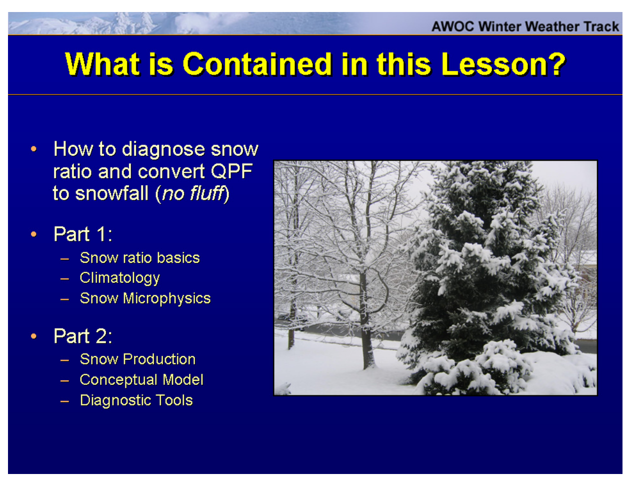


2. What is Contained in this Lesson?

Instructor Notes: The focus of this lesson is to assess potential snowfall given a forecast QPF. This will be done by diagnosing the most likely snow ratio and then applying that ratio to convert QPF into a forecast of snowfall. When combined with the previous IC-6 lessons, you will be able to fully diagnose the potential of a winter storm in terms of snowfall - for example, the diagnosis of snow as the precipitation type; secondly, its duration and intensity; thirdly, an understanding and ability to communicate forecast uncertainty; and lastly, with this lesson a means of understanding and expressing the amount and character of the snowfall itself.

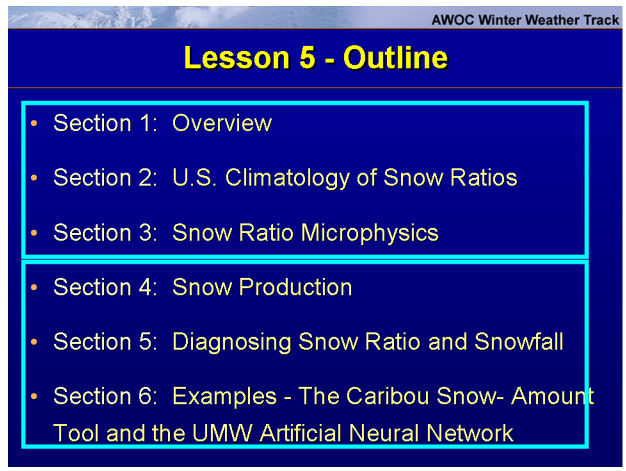
Student Notes:



3. Lesson 5 - Outline

Instructor Notes: This lesson is divided into 6 sections. Part 1 of this lesson will discuss the first 3 sections. Part 2 will cover the last three sections. Section 1: Overview; Section 2: U.S. Climatology of Snow Ratios; Section 3: Snow Ratio Microphysics; Section 4: Snow Production; Section 5: Diagnosing Snow Ratio and Snowfall; and Section 6: (Examples - The Caribou Snow-Amount Tool and the UMW Artificial Neural Network).

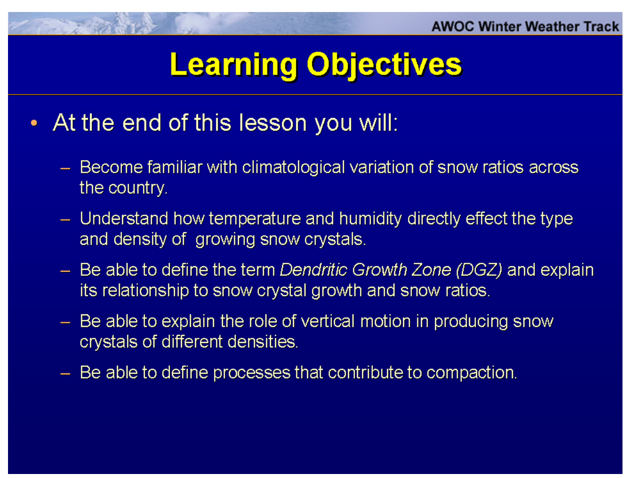
Student Notes:



4. Learning Objectives

Instructor Notes: The learning objectives for this lesson are to be able to identify the conditions of ice crystal growth in clouds, and how changes to crystal structure occur due to both sub-cloud processes and surface processes, including melting and compaction. Students should learn the long term averages of snow ratios and their variability to provide important background information on forecasting snowfall events and distributions.

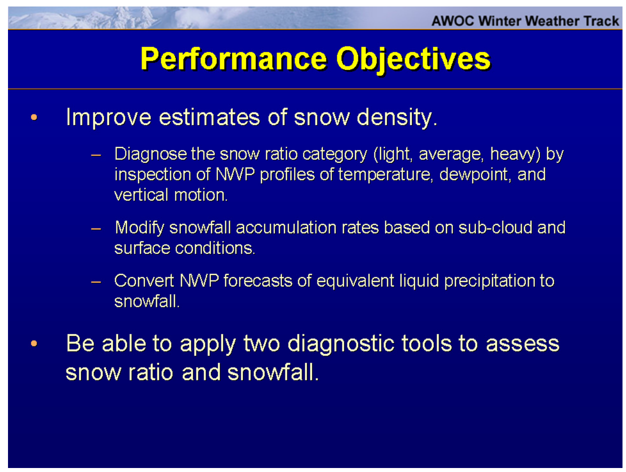
Student Notes:



5. Performance Objectives

Instructor Notes: The performance objectives for this lesson are to improve estimates of snow density. You should be able to do this by: diagnosing the snow ratio category (light, average, heavy) through inspection of NWP profiles of temperature, dewpoint, and vertical motion modifying snowfall accumulation rates based on sub-cloud and surface conditions and, converting NWP forecasts of equivalent liquid precipitation to snowfall. In addition, you should be able to demonstrate how to use two diagnostic tools to assess snow ratio and expected snowfall, the Caribou forecast tool and the UWM Neural Net.

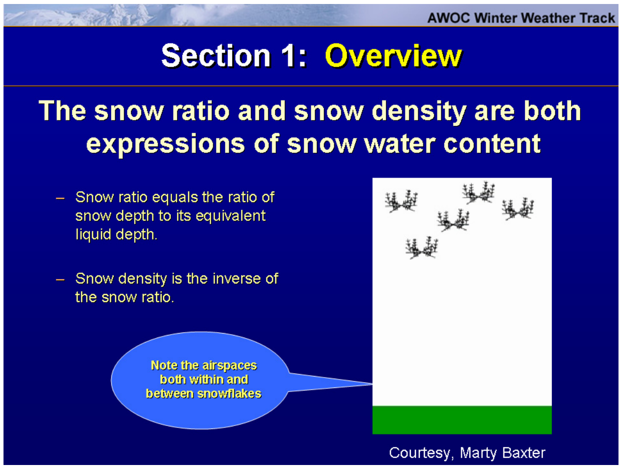
Student Notes:



6. Section 1: Overview

Instructor Notes: Let's review the definitions of snow ratio and snow density, which we'll use throughout the session. The snow ratio is the ratio of snow depth to its melted equivalent liquid depth. For example, a ten to one ratio (10:1) indicated that ten inches of snow fell for every inch of melted liquid equivalent, or a thirteen to one ratio indicated thirteen inches of snow fell for each inch of liquid equivalent. The snow density or water-to-snow ratio is the inverse of snow ratio, or the equivalent liquid depth divided by its measured snow depth. For example a 10:1 snow ratio would be equivalent to a snow density of 0.10. A low density snow would provide relatively high accumulations, and a high density snow would lead to low accumulations. Here, the animation illustrates the role of snow density in impacting accumulations. The density of a snowfall is determined by the amount of airspace between and within snowflakes.

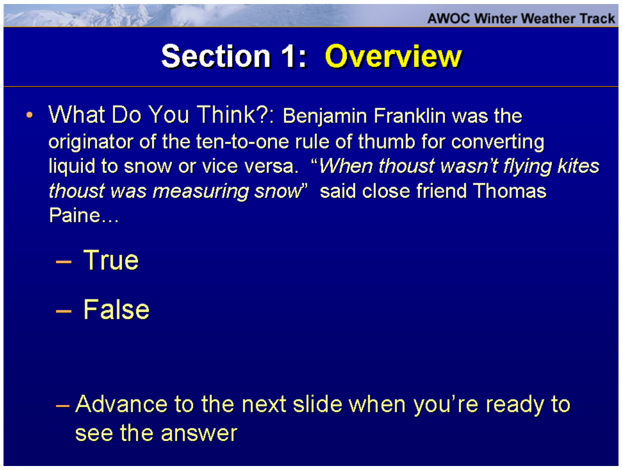
Student Notes:



7. What Do You Think?

Instructor Notes: Our first quiz question provides a little background on previous misguided attempts to determine a snow to liquid ratio. This is still one on the toughest operational problems we have, so let's explore further why we need better guidelines for determining the snow to liquid ratio.

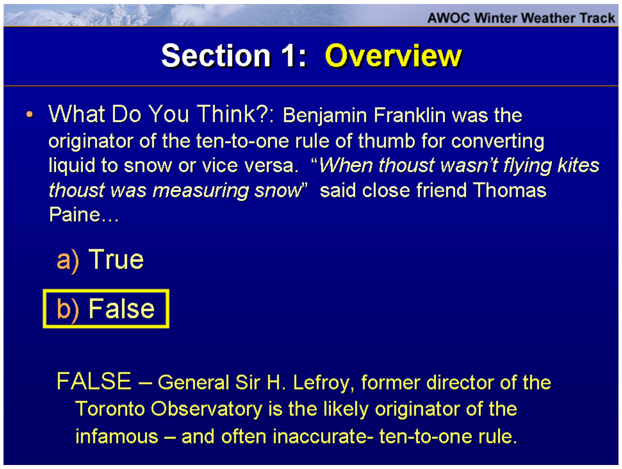
Student Notes:



8. Answer

Instructor Notes: The answer is false. General Sir H Lefroy, director of the Toronto observatory is the likely originator of the infamous, and often inaccurate, ten-to-one rule. Our first quiz question provides a little background on previous misguided attempts to determine a snow to liquid ratio. This is still one on the toughest operational problems we have, so let's explore further why we need better guidelines for determining the snow to liquid ratio.

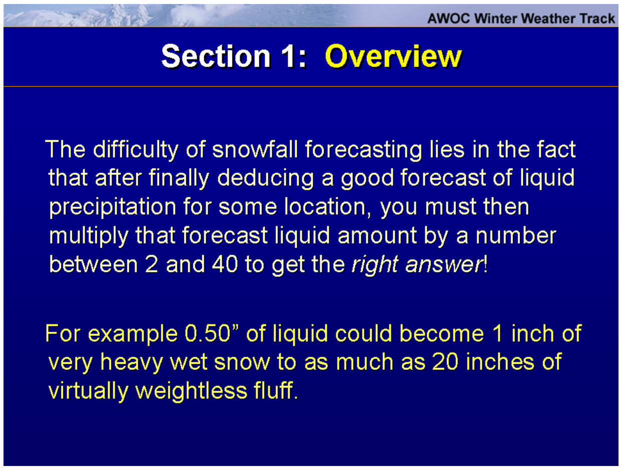
Student Notes:



9. Section 1: Overview

Instructor Notes: The difficulty of snowfall forecasting lies in the fact that after finally deducing a good forecast of liquid precipitation for some location, you must then multiply that forecast liquid amount by a number between 2 and 40 to get the right answer! For example 0.50" of liquid could become 1 inch of very heavy wet snow to as much as 20 inches of virtually weightless fluff.

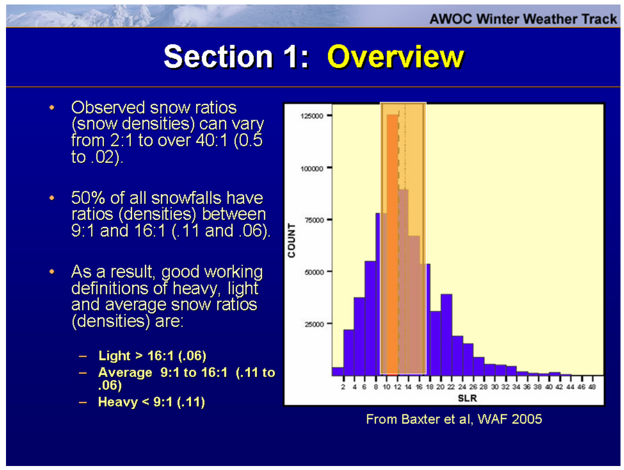
Student Notes:



10. Section 1: Overview

Instructor Notes: Let's review the total distribution of 30 years of observed snow to liquid ratios. Notice the well defined peak near 10:1 snow to liquid ratios and the wide range from 2:1 to over 40:1. Interviews with NWS forecasters have indicated instances in which the designated 10:1 ratio was the result of an estimate, rather than an actual measurement of melted snow and computation of the snow ratio based on the liquid equivalent, so we believe the peak is too high. While 50 percent of events have snow to liquid ratios between 9:1 to 16:1, notice the steep reduction in the number of events of snow to liquid ratios of less than 6:1 and also the much longer right tail of the distribution of higher ratios as you go above 20:1. This is reinforced by the average snow to liquid ratio nationwide is 13:1, as the snowier regions of the country over the long term average higher snow to liquid ratios. This distribution with well defined clustering of events between 9:1 and 16:1 snow ratios leads to working definitions of an average event within this range, with light density snow events (higher accumulations) are those greater than 16:1; average snow events are those between 9:1 and 16:1; and heavy events, or those wet snows with high water content, less than 9:1. The orange outlined area highlights the peak cluster of events between 9:1 and 16:1.

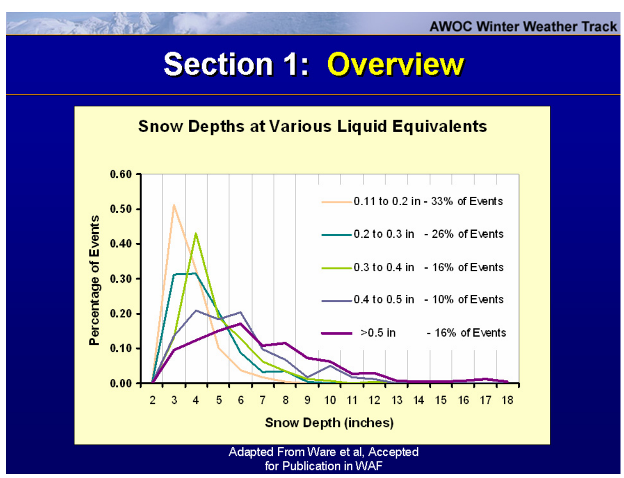
Student Notes:



11. Section 1: Overview

Instructor Notes: This figure shows the range of snow depths for ranges of liquid equivalent precipitation. Notice that as you go toward higher liquid amounts, the total range of observed snowfall increases. This means there is both considerable variability in snow ratios from event to event and also during an event, reinforcing the importance of determining snow-ratio in predicting snowfall accumulations. Note the purple contour for half inch or greater liquid equivalent amounts resulted in snowfall reports ranging from 2 to 18 inches.

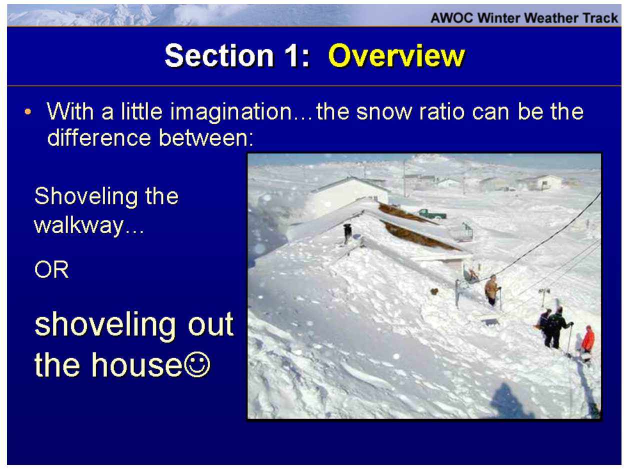
Student Notes:



12. Section 1: Overview

Instructor Notes: And thus you can see that variations in snow to liquid ratio lead to large variations in both predicted and observed snowfall.

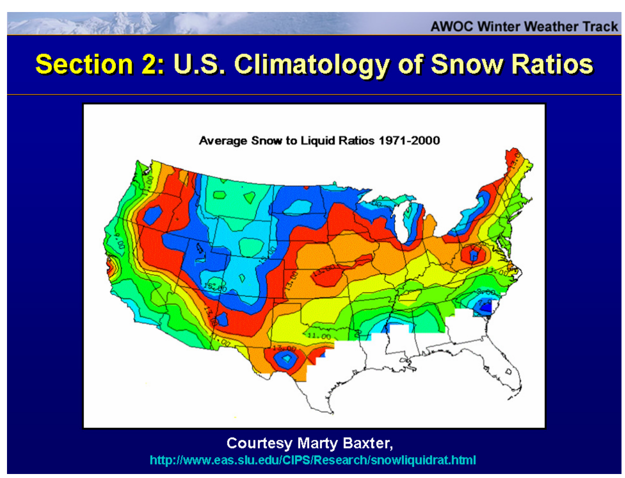
Student Notes:



13. Section 2: U.S. Climatology of Snow Ratios

Instructor Notes: We previously referred to the outdated notion of the 10:1 rule for snow ratios, as the national average snow ratio is near 13:1. Here, you can see the geographical distribution indicating many of the locations which receive heavy snow, such as around the Great Lakes, have higher ratios. The lower ratio areas are either warmer locales or close to where cyclones ingest relatively warm maritime air, such as in the coastal areas of the mid Atlantic and New England, and over the ranges of northern CA and west OR and WA.

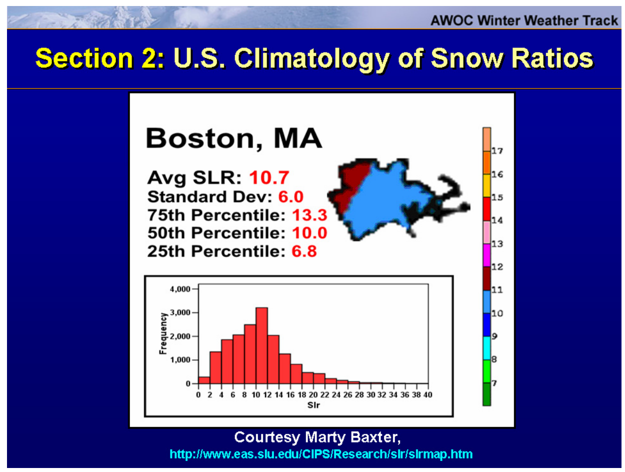
Student Notes:



14. Section 2: U.S. Climatology of Snow Ratios

Instructor Notes: Here we show a sample of four National Weather Service Forecast Office snow to liquid ratios, the standard deviation of the amounts for each area of responsibility. Here is the snow to liquid ratio distribution for Portland OR. It's location in western OR and proximity to the Pacific Ocean lead to relatively low snow ratios and low variability. In contrast, look at the higher snow ratios and higher variability at Great Falls MT. Buffalo NY has a similar average of ratios but a wide spread in its distribution. And here the Boston MA area has lower than average snow to liquid ratios and variability. Look at the website at the bottom of the page to see how your CWA compares to these examples (http://www.eas.slu.edu/CIPS/Research/slr/slrmap.htm).

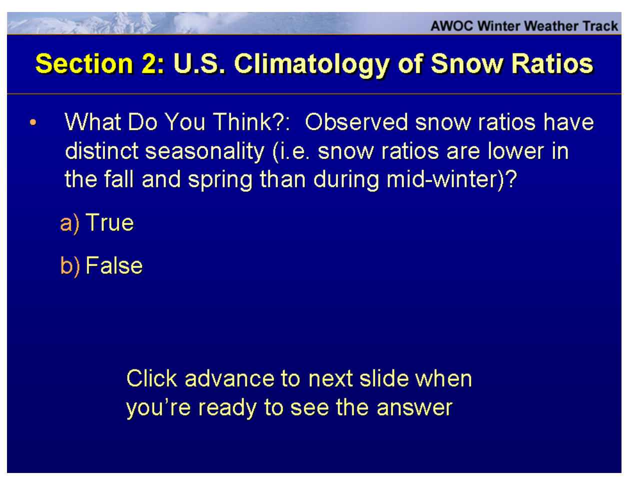
Student Notes:



15. What do you think?

Instructor Notes: Here is a quiz question on whether snow ratios change with the seasons.

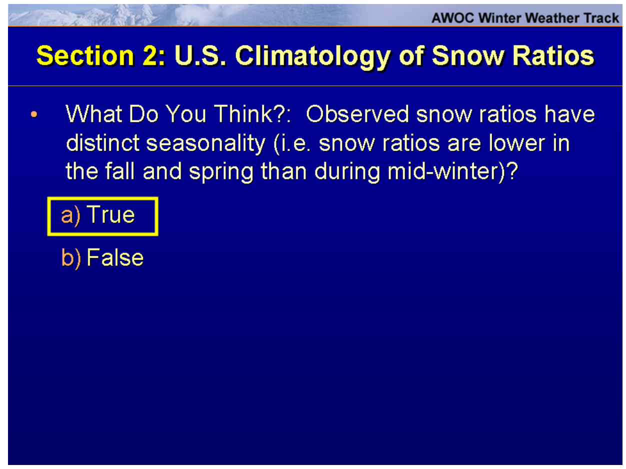
Student Notes:



16. Answer

Instructor Notes: The answer is true and we'll review the changes that occur over the seasons.

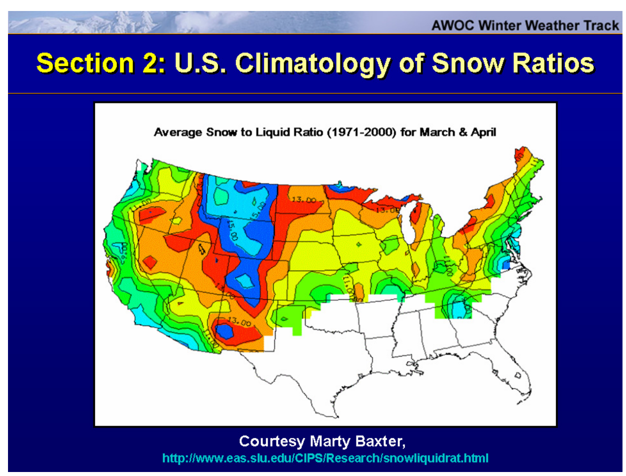
Student Notes:



17. Section 2: U.S. Climatology of Snow Ratios

Instructor Notes: Here are the values for fall. Higher values are inland and in the Rockies. Warm surface temperatures lead to relatively small values on the coast. Here are the peak winter ratios, which are the highest of all seasons matching the coldest time of the year; about 3 times that of fall. Springtime ratios return to smaller values as solar angle increases and so does melting.

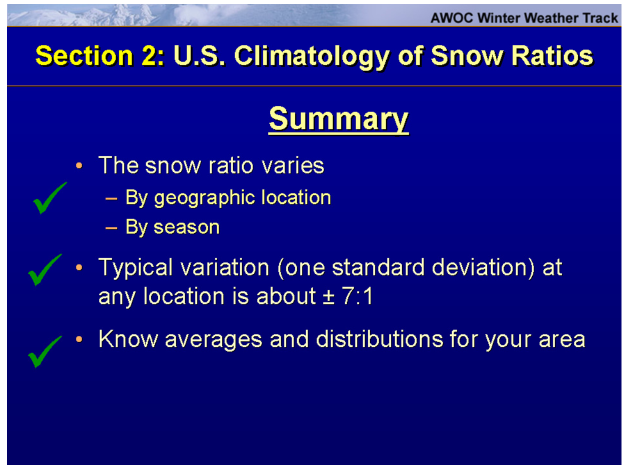
Student Notes:



18. Section 2: U.S. Climatology of Snow Ratios

Instructor Notes: We have seen that the snow ratios vary by event, season, and temperature and solar radiation impacts, among others. The significant event to event variability is reinforced by a standard deviation near 7 across the contiguous US. A station whose average snow to liquid ratio is 13 would have about two thirds of its events with snow ratios between 6:1 and 20:1. Knowing these averages and distributions for each area is important in determining the most likely snow ratios for each event.

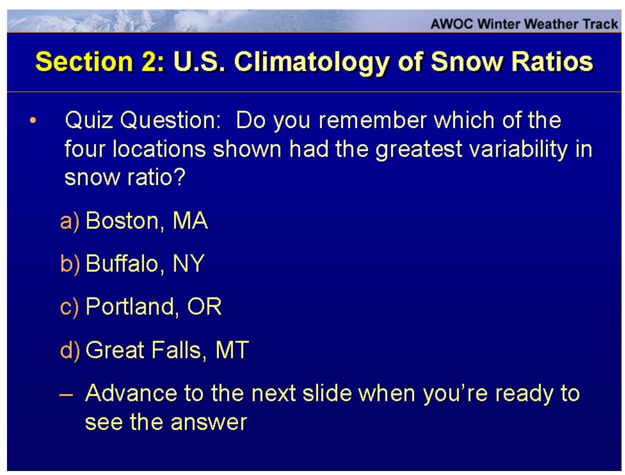
Student Notes:



19. Quiz Question

Instructor Notes: Do you remember which of the four locations shown had the greatest variability in snow ratio?

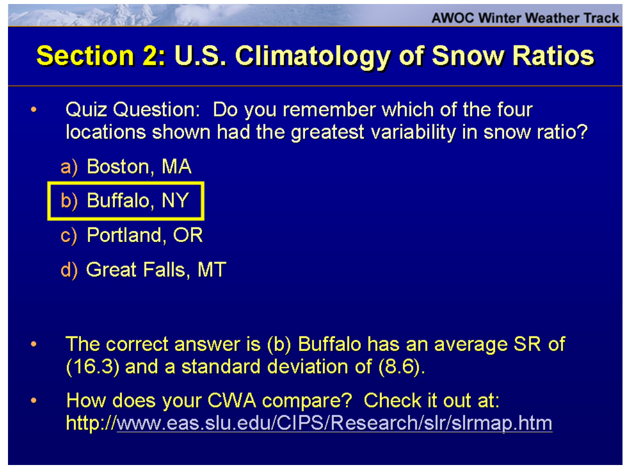
Student Notes:



20. Section 2: U.S. Climatology of Snow Ratios

Instructor Notes: The station with the most variability (highest standard deviation) in snow ratios among those in the contiguous US is Buffalo NY, which results from a wide variety of situations in which snowfall occurs, from synoptic events to mesoscale events.

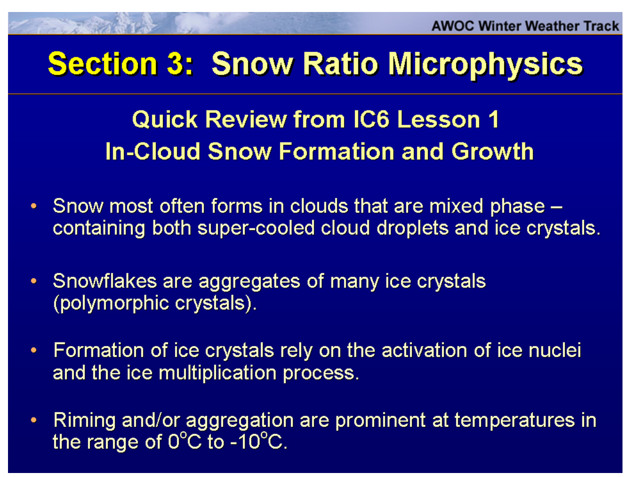
Student Notes:



21. Section 3: Snow Ratio Microphysics

Instructor Notes: In section 3, the discussion will focus on snow growth within clouds including preferred crystal habit or type, growth rates, and associated snow ratios of some common aggregates. I will also briefly discuss the effects of sub-cloud and near surface physics that can alter the snow ratio, but before we discuss snow microphysics in detail, let's take a minute to review some basic cloud microphysics from lesson 1 of IC6. The first is that snow forms in mixed phase clouds, that is clouds that contain both water and ice crystals. Snowflakes are aggregates of ice or snow crystals. The aggregates can be either homogenous or heterogeneous that is made up of just one type or several types of ice crystals. The activation of ice-nuclei at temperatures colder than -8 degrees C is an important key to the formation of ice crystals and in initiating the ice multiplication process. And lastly, ice crystal riming is often prominent at temps from 0 to -10 degrees C.

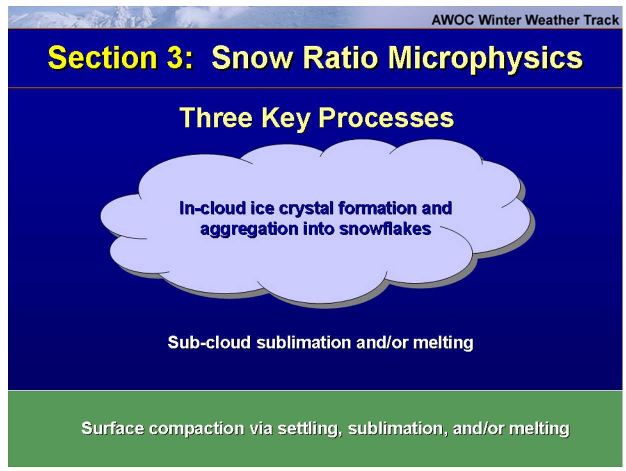
Student Notes:



22. Section 3: Snow Ratio Microphysics

Instructor Notes: Snow microphysics can be broken down into three key processes: 1) The first is the in-cloud formation of ice crystals which depend primarily upon temperature and humidity. 2) Below the cloud sublimation or partial melting can occur - both of which lead to higher snow density. 3) And once on the ground – settling, sublimation and/or melting can again lead to lower ratios or a denser snowfall.

Student Notes:



23. Section 3: Snow Ratio Microphysics

Instructor Notes: This diagram from SnowCrystals.Com (a great web site) shows how ice crystal habit or type is a function of both temperature and humidity. Temperature controls whether the crystal will be more plate or column like while humidity controls the spatial extent of the crystal. Temperature is depicted here along the X axis in degrees C, while the y axis represents humidity with respect to saturation over ice (i.e. 0.1 is 100.1% RH with respect to ice). At relatively low supersaturation – ice crystal habits tend to be more compact taking on the shape of prisms or plates depending upon the temperature at which they form. On the other hand, at higher degrees of supersaturation, crystals tend to branch forming star shaped crystals called dendrites or needle like structures, again the shape, needle or dendrite, depends on the temperature at which the crystal is growing. The potentially largest and least dense crystals form at temperatures between -10 and -20 degrees C. These crystals are called stellar dendrites. In fact, I like to refer to this temperature zone as the “Dendritic Growth Zone”. It has some other interesting properties with respect to snow formation that we’ll discuss in just a minute.

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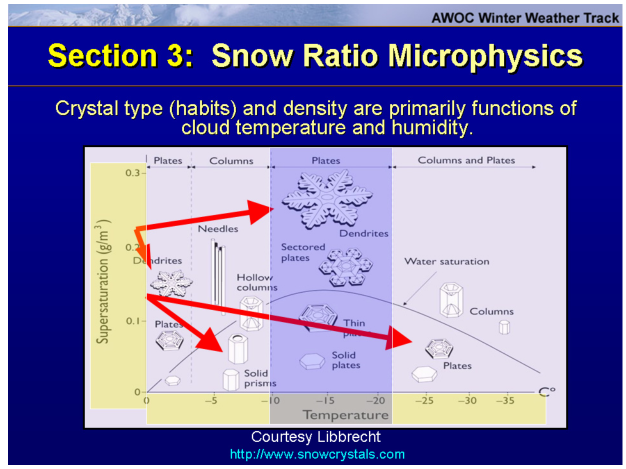
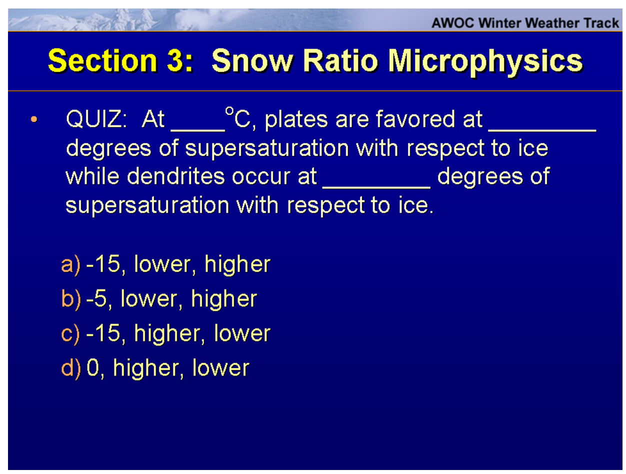


24. Quiz Question

Instructor Notes: Quiz time – I'll give you a few seconds to consider this one. When you've got the answer – proceed to the next slide.

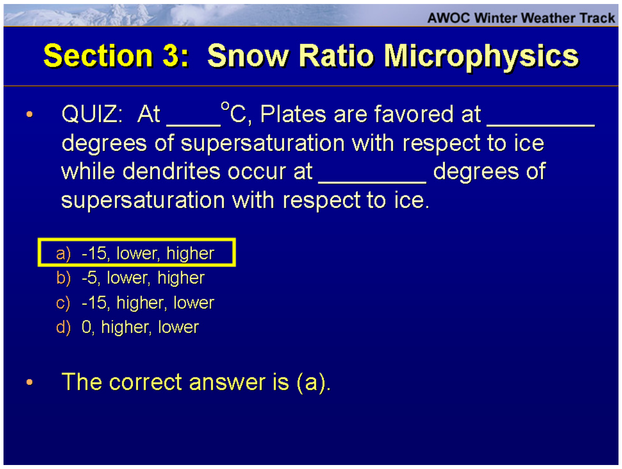
Student Notes:



25. Section 3: Snow Ratio Microphysics

Instructor Notes: Here is the answer to the quiz question.

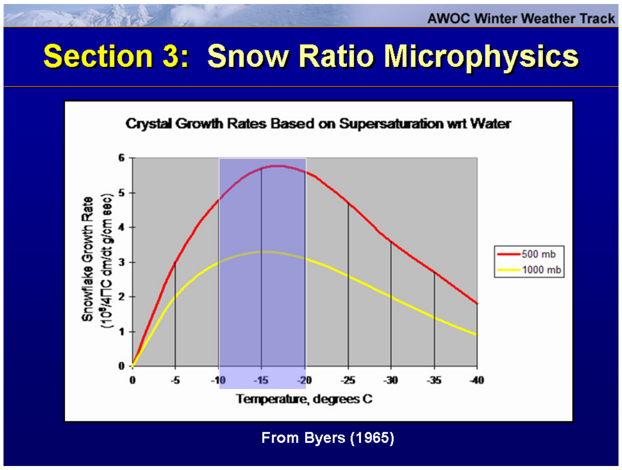
Student Notes:



26. Section 3: Snow Ratio Microphysics

Instructor Notes: This diagram depicts the growth rate of crystals as a function of temperature. Temperature decreases along the X axis while growth rate increases along the Y axis. The yellow curve depicts growth rates at pressures of 1000 mb while the red curve depicts growth rates at 500 mb. Here I have highlighted the Dendritic Growth Zone (DGZ), notice how well it correlates to the peak of the two curves. That's another special property of the DGZ that dendrites are spatially large (low density) and are the fastest growing crystal given sufficient degrees of supersaturation.

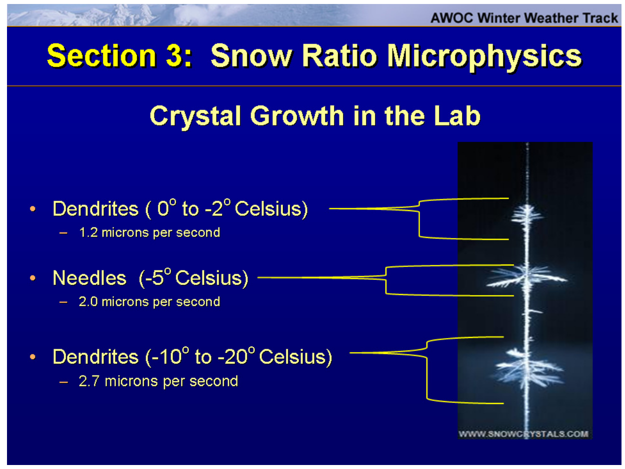
Student Notes:



27. Section 3: Snow Ratio Microphysics

Instructor Notes: Now let's take a look at growth rates in the lab. In the picture at right, crystals are being grown on a fine wire hanging inside of a diffusion chamber. The temperature is highly stratified in the chamber ranging from above freezing at the top of the picture to colder than -20 degrees C at the bottom. Humidity is also carefully controlled to maintain supersaturation with respect to ice throughout the chamber. Overall, growth rates in the laboratory agree well with theory. The observed maximum growth rate in the chamber of 2.7 microns/second occurred at -15 degrees C. What is interesting is the quantum like growth that is seen here with pronounced crystal habit spikes as one moves from slow dendritic growth near freezing...to brisk columnar growth with needles at -5 degrees C...and then rapid dendritic growth in the DGZ.

Student Notes:



28. Quiz Question

Instructor Notes: Here's another quiz question for you. When you've got the answer, proceed to the next slide.

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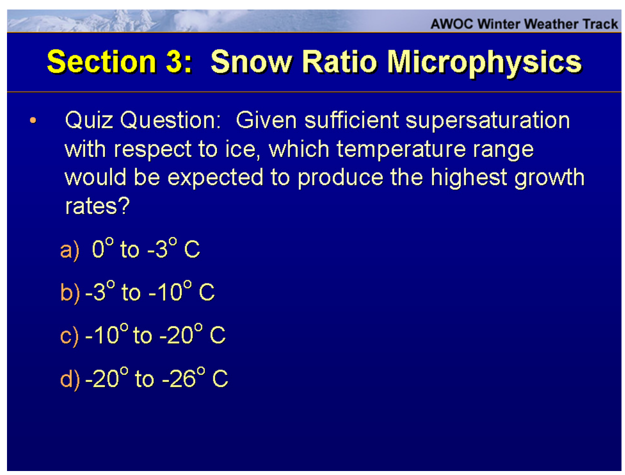
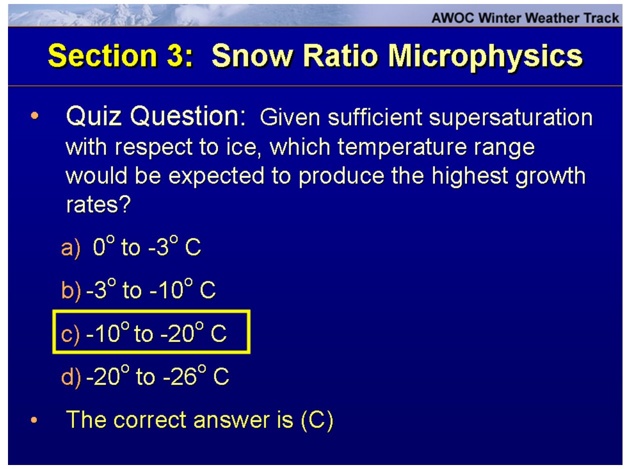


29. Answer

Instructor Notes: The correct answer is C. The DGZ supports the fastest crystal growth rates…and also the lowest density crystals.

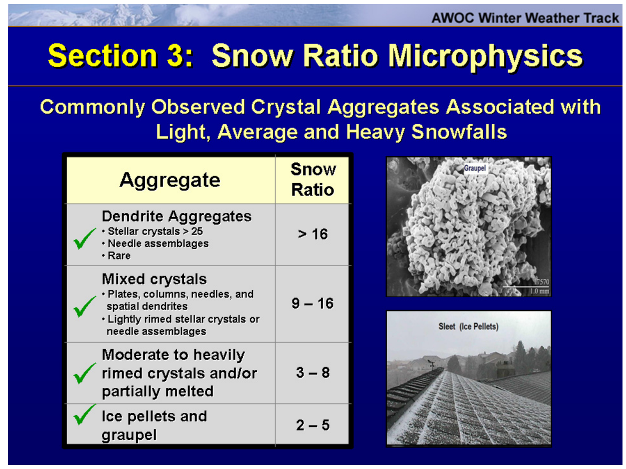
Student Notes:



30. Section 3: Snow Ratio Microphysics

Instructor Notes: Okay, we've spent some time looking at the growth of ice crystals. Now let's relate ice crystal to the snow ratio. This table is adapted from work by Ivan Dube of the Canadian Weather Service. I followed on Dube's observations for a three year period in northern Maine. This table is not meant to be absolute but more of a guideline to help one map observed snowflakes to a likely snow ratio once the snow has fallen. Of course surface effects like melting must also be considered in this mapping. Dendritic snowflakes are typically the lightest with snow ratios for stellar dendrites exceeding 25:1. These kind of snows are common with cold convective clouds occurring in the NW quadrant of a winter cyclones or associated with lake or ocean effect snows. Common in many overrunning situations, these snowflakes contain a variety of ice crystals including bullets, plates, spatial plates, dendrites, needles and columns. Spatial dendrites are actually a crystal hybrid. They start out as columns or small assemblage of plates...that subsequently encounter temperature and humidity conditions conducive to dendritic growth. Also, these snowflakes are quite often slightly rimed. Mixed crystals will in general...fit more tightly together resulting in average snow ratios of between 9 and 16 to 1. Moderate to heavy riming of snowflakes will result in low snow ratios of less than 9:1. Depending on the kind of snowflakes falling into the cloud riming layer – observed snowflakes can range from sleet like snow grains to monster sized wet snowflakes. Classically, heavily rimed flakes are associated with elevated warm layers containing near freezing temperatures...and can be thought of as a warmer subset of the warm frontal or overrunning scenario. Ice pellets and graupel have ratios smaller than 5:1. Graupel is typically the result of extremely rimed snowflakes and is often associated with convective clouds that intersect the -10 to -20 degrees C temperature range. Sleet on the other hand is the result of partial melting and subsequent re-freezing of snowflakes.

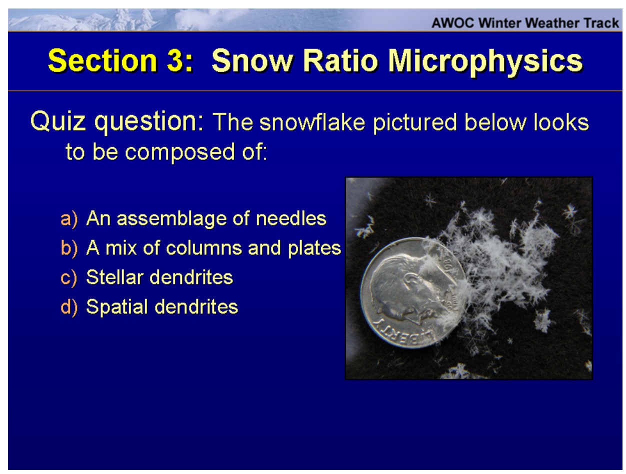
Student Notes:



31. Quiz Question

Instructor Notes: When you've got the answer, proceed to the next slide.

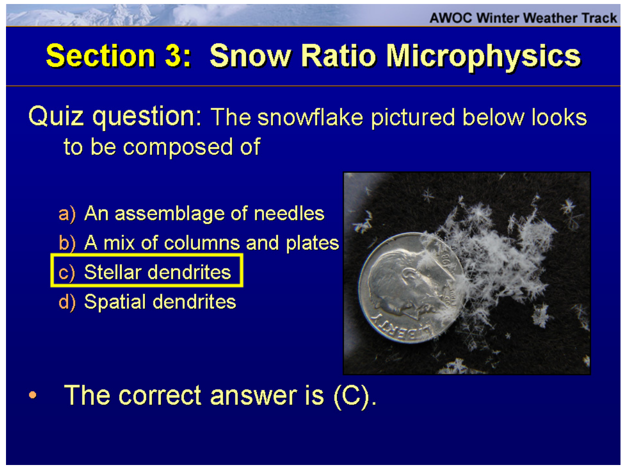
Student Notes:



32. Answer

Instructor Notes: The correct answer is C. This picture is of a single snowflake composed of stellar dendrites. It fell as part of a brief snow shower associated with a band of puffy wintertime cumulus. The cumulus had bases of about 2,500 ft. with tops under 10,000 Ft.

Student Notes:



33. Section 3: Snow Ratio Microphysics

Instructor Notes: Now I'll change gears and talk about the sub-cloud and surface effects. This picture of a turbulent looking sky was taken about 15 minutes before light snow began. This situation occurred with steep lapse rates and dry air below cloud base. As snowflakes at the leading edge of the precipitation sublimated, they cooled this layer creating shallow super-adiabatic lapse rates between the layer just cooled and the layer immediately below. Auto-convective currents formed within this layer, giving the turbulent look to the leading edge of the falling snow. More generally, sublimation and melting are associated with dry and/or warm layers below cloud base. This process can cool an initially warm layer below freezing; the wet bulb profile is often a good discriminator of such a possibility. In terms of the snow ratio, both sublimation and melting will increase the snow density. For sublimation, look for advection of dry air at or below the cloud base. This is common on the leading edge of WAA where snow formation may be above 10,000ft. Also look for subsiding air at or near the surface.

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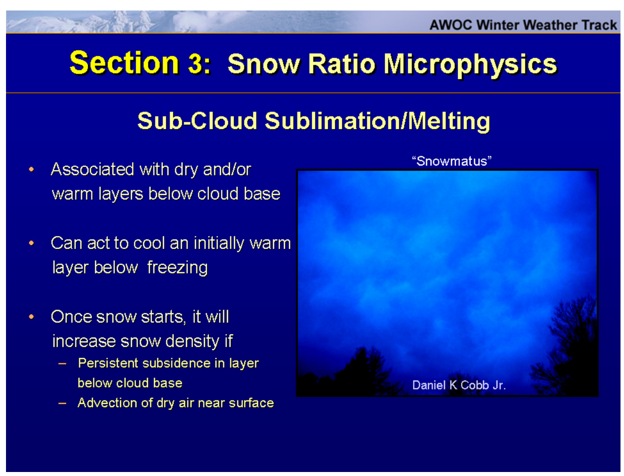
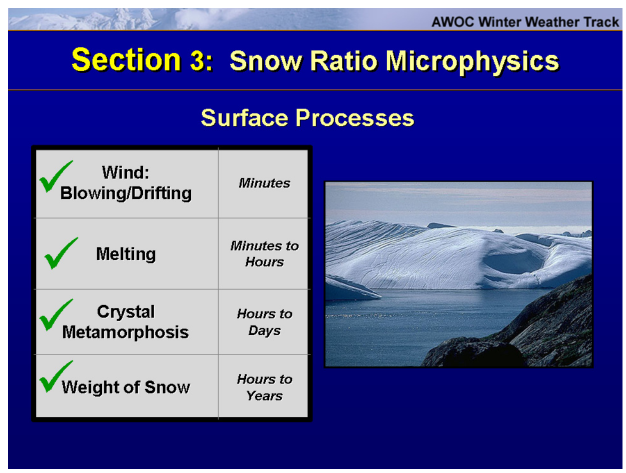


34. Section 3: Snow Ratio Microphysics

Instructor Notes: Surface processes can act very quickly or very slowly...and in general all act to lower observed snow ratios. Here...we are mainly concerned with processes that affect the snow ratio while the storm is in progress...that is between 6 hourly synoptic snow measurements or at most...the 24 hr. cooperative observer measurements. Through blowing and drifting - Wind causes spatial crystals like dendrites to fracture into smaller more compact pieces which lowers snow-ratios. This process occurs very quickly – as the snow falls. Partial melting of fallen snow can occur almost immediately with temperatures near freezing. Crystal metamorphosis describes the collapse of spatial crystals into more dense forms. Metamorphosis is a slower process which occurs most rapidly as temperatures approach freezing…but for our discussion...it is generally more of a concern for the 24 hr. cooperative observations. Compaction of fallen snow can also occur as crystals in the lower layers of newly fallen snow fracture and are pushed together by the weight of new layers above. This can happen quickly or slowly depending upon the crystal structures, temperatures, and accumulation rates.

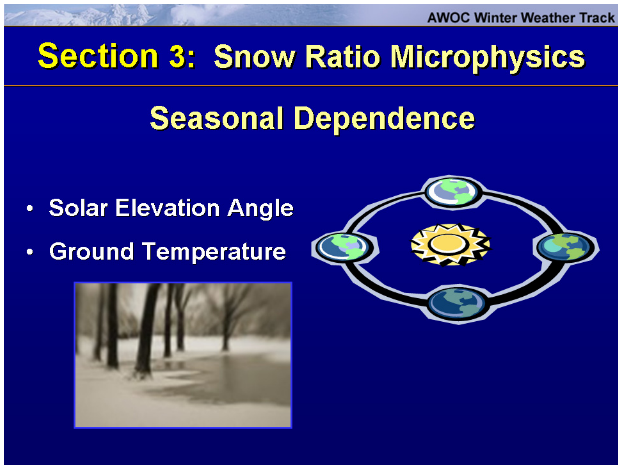
Student Notes:



35. Section 3: Snow Ratio Microphysics

Instructor Notes: We talked about seasonal dependence in section 2 – climatologies – but wanted to briefly discuss it once again in this section. In general – high solar elevation angles that are most prominent in late winter and early spring along with warm ground temperatures that are common in the fall can both act to accelerate surface processes like melting, crystal metamorphosis, and sublimation.

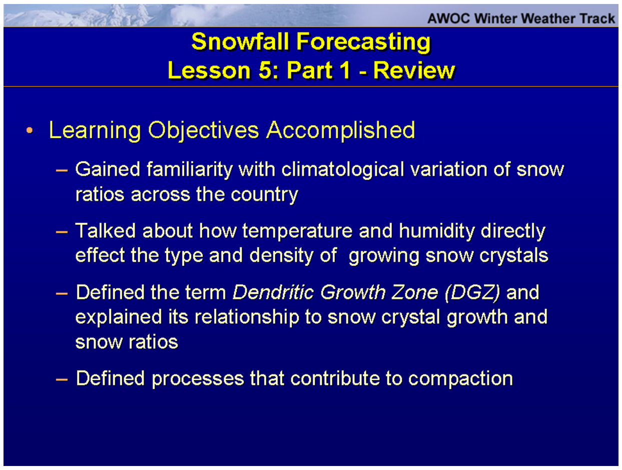
Student Notes:



36. Snowfall Forecasting Lesson 5: Part 1 - Review

Instructor Notes: What we discussed on this part of IC 6 lesson 5, we gained familiarity with climatological variation of snow ratios across the country. We talked about how temperature and humidity directly effect the type and density of growing snow crystals. We defined the term, Dendritic Growth Zone (DGZ) and explained its relationship to snow crystal growth and snow ratios. We defined processes that contribute to compaction.

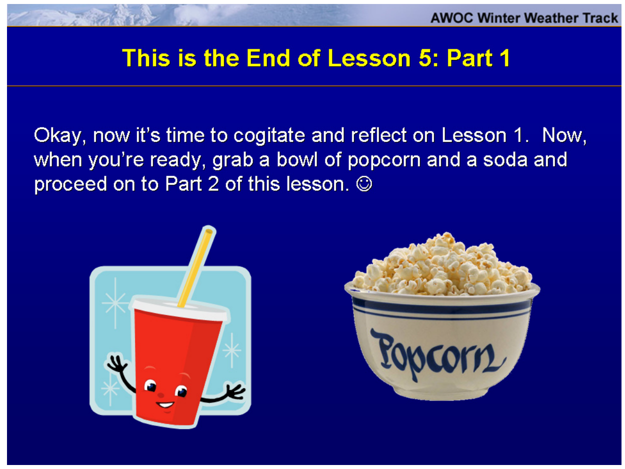
Student Notes:



37. Good Bye

Instructor Notes: This is the end of Lesson 5, Part1. When you are ready, proceed to Part 2 of this lesson.

Student Notes:



38. Recommended Web-Based References

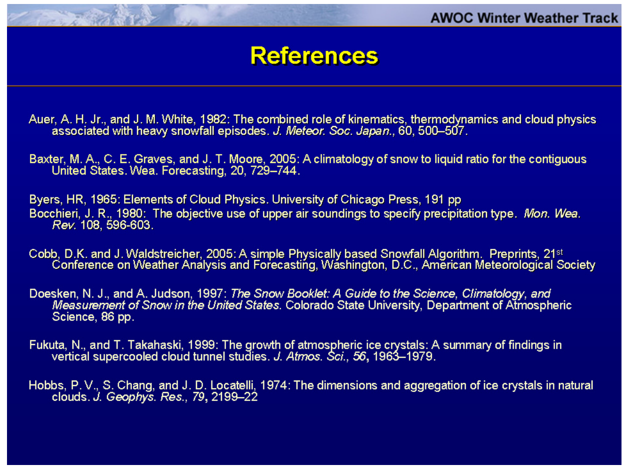
Instructor Notes: This slide is the first of three pages of references cited in the lesson.

Student Notes:

39. References

Instructor Notes: This slide is the second of three pages of references cited in the lesson.

Student Notes:



40. References

Instructor Notes: This slide is the third of three pages of references cited in the lesson.

Student Notes: